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Field Independence associates with mathematics and science performance in 5- to 10-year-olds after accounting for domain-general factors

Running title

Field independence, mathematics and science

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Conflict of interest statement

The authors have no conflict of interest to declare.

Abstract

Field independence describes the extent to which individuals are influenced by context when trying to identify embedded targets. It associates with cognitive functioning and is a predictor of academic achievement. However, little is known about the neural and cognitive underpinnings of field independence which lead to these associations. Here we investigated behavioural associations between two measures of field independence (Children's Embedded Figures Test (CEFT) and Design Organisation Test (DOT)) and performance on mathematics (reasoning and written arithmetic) and science tests (reasoning and scientific inquiry) in 135 children aged 5-10 years. There were strong associations between field independence and mathematics and science, which were largely explained by individual differences in age, IQ, and verbal working memory. However, regression analyses indicated that after controlling for these variables, the CEFT explained additional variance on the mathematical reasoning and science tests, whereas the DOT predicted unique variance on the written arithmetic test.

Keywords: field independence, mathematics, science, child development, executive function

Introduction

Field independence (FI) is the extent to which individuals are able to separate a target from its context. Positive associations between FI and academic success have been found in mathematics in children aged 6 to 10 years (Buriel, 1978) and adolescents aged 12 to 14 years (Alamolhodaie, 2002; Azari, Radmehr, & Mohajer, 2013), and in science in adolescents aged 13 to 16 years (Tinajero & Paramo, 1997) and 17 to 18 years (Leo-Rhynie, 1985). However, little is known regarding the specific cognitive processes which underlie these associations with mathematics and science, or whether these relationships are mediated by individual differences in general cognitive ability and executive functions. The dual aims of this study were to examine the domain-general factors implicated in FI, and to investigate how different FI tasks associate with performance on mathematics and science in primary school children, considering overlapping variance with age, IQ, working memory and inhibitory control.

Measures of field independence

FI is usually measured using a version of the Embedded Figures Test (EFT; Witkin et al., 1971), or the Block Design task (Wechsler, 1974). In the EFT, participants must locate a simple target shape within a complex stimulus. When a target is embedded within a context, it becomes hidden due to shared lines, overlapping colours, and distracting patterns (De-Wit, Huygelier, Van der Hallen, Chamberlain, & Wagemans, 2017; Poirel, Pineau, Jobard, & Mellet, 2008; Van der Hallen, Chamberlain, De-Wit, & Wagemans, 2018). This contrasts with visual search paradigms where a target is surrounded by distractor elements but is not embedded within a context (Wolfe & Horowitz, 2017) and matching tasks where a target shape has to be identified amongst a number of distinct, non-overlapping choices (Li, Wu, Zhu, & O'Boyle, 2014). The process of identifying the target

within its context is known as disembedding. In the Block Design task, participants must partition a pattern into a grid of squares, and then match each segment of the grid with a choice of simple designs. The pattern becomes harder to segment when the design spreads over a grid boundary, as the large-scale pattern has to be overcome to identify the individual elements. This process is known as segmenting (Schorr, Bower, & Kiernan, 1982; Shah & Frith, 1993). It differs from disembedding because it is guided by fixed gridlines, whereas disembedding involves a search process to identify the boundaries of the target. Despite these differences, in a study with university students, both tasks loaded onto a single factor (Milne & Szczerbinski, 2009). In both tasks, individuals with greater accuracy or faster reaction times are described as being field independent, and those with lower accuracy or slower responses are described as being field dependent.

Performance on the EFT has been shown to associate with global and local processing (Poirel et al., 2008), spatial thinking (Rémy & Gilles, 2014) and orientation abilities (Boccia, Piccardi, Di Marco, Pizzamiglio, & Guariglia, 2016), as well as general cognitive abilities (Flexer & Roberge, 1980; Miyake, Witzki, & Emerson, 2010). This has resulted in a lack of clarity about what FI represents (Evans, Richardson, & Waring, 2013). The literature sometimes describes FI in perceptual terms, where success is related to overcoming the Gestalt principles of proximity, similarity, and good continuation (De-Wit et al., 2017; Van der Hallen et al., 2018). However, it is also described in cognitive terms, as the extent to which individuals are able to analyse and restructure a given stimulus to solve a problem that requires details to be decontextualised (Pithers, 2002; Rémy & Gilles, 2014; Witkin, Moore, Goodenough, & Cox, 1977). In both the EFT and Block Design tasks, the visual stimulus needs to be reinterpreted by being parsed into smaller elements. It is therefore likely that both perceptual and cognitive processes determine an individual's FI.

There is limited understanding regarding the neural correlates underpinning FI. There is evidence for greater activation in the frontoparietal cortex in tasks involving disembedding in adolescents aged 12 to 16 (Manjaly et al., 2003), as well as in adults (Manjaly et al., 2007; Walter & Dassonville, 2011). However, the precise cortical locations vary between studies depending on both the experimental task and comparison condition. The hemispheric lateralisation of activations also varies by task, with left posterior parietal activations in easier tasks (Manjaly et al., 2007) but bilateral activations in more challenging tasks (Walter & Dassonville, 2011). Left hemispheric activation may reflect local visual processing (Manjaly et al., 2007; Weissman & Woldorff, 2005) during disembedding. In more complex tasks, activation in the right temporoparietal junction, precuneus and insula may reflect the involvement of executive control in co-ordinating bottom-up and top-down processing (Walter & Dassonville, 2011). This supports the suggestion that both perceptual and cognitive processes are involved when completing FI tasks.

Research has consistently shown a developmental change from field dependence to FI in children and adolescents aged 3 to 17 years (Amador-Campos & Kirchner-Nebot, 1997; Busch et al., 1993; Cairns, Malone, Johnston, & Cammock, 1985; Glynn & Stoner, 1987; Goodenough & Eagle, 1963; Witkin, Goodenough, & Karp, 1967), despite variations in the test stimuli used and task differences in memory load. Gender differences have also been identified, with males achieving higher accuracy than females in the EFT in primary school-age children (Amador-Campos & Kirchner-Nebot, 1997; Cairns et al., 1985; Jantan, 2014), adolescents aged 11 to 14 years (Flexer & Roberge, 1980), and adults (Witkin et al., 1977), which is suggestive of higher FI in males than in females.

Association with academic success

Mathematics and science both involve pattern detection and analysis, as well as the application of concepts across many contexts (Bressan, 2018; Wei, Yu Shattock, McCracken, & Blackorby, 2013), e.g. sharing marbles between three friends and dividing a cake into three equal pieces, or considering evaporation of water from a puddle and from clothes on a washing line. In addition, an understanding of the relationships between wholes and parts is important for mathematical tasks (Baroody, 2000) and for science understanding (Project 2061, 2009). This suggests that an ability to focus on details and to decontextualise information may be advantageous to mathematics and science performance.

A consistent picture has emerged of a positive association between FI, as measured by the Group EFT, and academic success in children and adolescents, particularly in mathematics, using general (Alamolhodaie, 2002; Azari et al., 2013; Buriel, 1978; Roberge & Flexer, 1983; Tinajero & Paramo, 1997; Tinajero, Páramo, European, June, & Fernanda, 1998) or specific measures. In a study with university students, Zhang (2004) found that FI only associated with the geometry subsections of their mathematics measure, while other studies found associations with word problems in adolescents (Alamolhodaie, 2002; Azari et al., 2013). The shared visuospatial processing demands of geometry problems and FI tasks may underlie their associations. In contrast, word problems require mathematical information to be taken out of the 'real-world' context, and may therefore be related to FI tasks requiring disembedding.

Fewer studies have investigated associations between FI and science achievement. Higher EFT scores (reflecting greater FI) have been achieved by those studying science compared with non-scientific disciplines at the undergraduate level (Billington, Baron-Cohen, & Wheelwright, 2007; Derussy & Futch, 1971) and in adolescents aged between 13 and 18 years (Leo-Rhynie, 1985; Tinajero & Paramo, 1997), with possible differences

detected according to topic, e.g., geology being more associated with FI than evolution in undergraduates (Lawson, 1983).

Field independence, IQ and executive functions

Although there is evidence for a positive relationship between FI and academic achievement, there is limited understanding about the cognitive processes which underpin this association. A number of studies report a positive association between FI and IQ (e.g. Flexer & Roberge, 1980; Swyter & Michael, 1982), and importantly that FI still explained performance in mathematics after controlling for IQ (Azari et al., 2013; Satterly, 1976; Tinajero & Paramo, 1997). In contrast, a recent study found no group-level relationship between FI and visuo-spatial IQ in a sample of university students (Li et al., 2014).

Associations between FI and academic achievement may also be mediated by shared associations with executive functions, particularly working memory (WM) and inhibitory control (IC). WM describes the fixed, limited capacity to briefly hold and manipulate information in mind to complete a task (Gathercole, Pickering, Knight, & Stegmann, 2004). IC refers to the ability to ignore irrelevant distractors or to stop a prepotent but incorrect response (Miyake et al., 2000). There is substantial development of IC in preschool, whereas the development of WM is more protracted (Best & Miller, 2010). In order to successfully complete the EFT, participants have to hold the target shape in mind, whilst they monitor the complex figure and ignore distractor shapes (Evans et al., 2013; Jia, Zhang, & Li, 2014). Research has identified a positive association in adults between EFT performance and verbal WM (Guisande, Soledad Rodríguez, Almeida, Tinajero, & Fernanda Páramo, 2008), visuo-spatial WM (Miyake et al., 2010), and IC (Imanaka, Kakigi, & Nakata, 2017). Furthermore, in

pre-school children, better performance on the Block Design task associated with higher verbal WM scores (Alloway & Alloway, 2010).

This association between executive functions and FI is supported by evidence from neuroimaging. Adults completing the EFT showed activation in a wide network of brain regions including bilateral parietal areas and right dorsolateral prefrontal cortex, interpreted as reflecting the involvement of visuo-spatial WM (Ring et al., 1999). A separate study in children aged 7 to 12 years similarly showed bilateral parietal activation but dorsolateral prefrontal cortex activation was located in the left hemisphere, which could reflect greater use of verbal WM strategies (Lee et al., 2007). Consistent with recruitment of IC to suppress the global form (Lux et al., 2004), higher performance on the EFT in adults associated with greater activation in the inferior frontal gyrus and insula (Walter & Dassonville, 2011), and in children, activation in the anterior cingulate cortex was observed during the EFT but not during the control matching task (Lee et al., 2007).

To summarise, research has identified a positive association between FI and academic measures. However there is limited understanding about the underlying processes which explain this association, and whether these explain any changing associations with FI through development. The first aim of this study was to explore the extent to which performance on FI tasks can be explained by variation in age, IQ, WM and IC in childhood, and therefore gain a clearer understanding of FI in terms of its underlying processes. We predicted increased FI with age, and that all three of these aspects of cognition would predict FI, with a greater link with verbal WM than visuospatial WM (Lee et al., 2007). The second aim was to establish whether FI associated with achievement on mathematics and science tests, and whether these associations are explained by individual differences in age, IQ, WM and IC. We predicted that FI would associate with higher

mathematics and science scores, and that much of this relationship would be explained by overlapping variance associated with IQ and executive functions. We also predicted that mathematical reasoning and science would more closely associate with disembedding than segmenting due to the need to separate concepts from the context of the question. Finally, as executive function skills improve considerably during the primary school years (Best & Miller, 2010), and as the demands of the mathematics and science curricula also change, we were interested in whether observed associations between FI, executive functions, and mathematics and science achievement differed between school Years (see Supporting Information for these analyses). To test this, we collected data from children in three different primary school Years.

Method

Participants

The study was approved by the local ethics committee. Participants were recruited from a single community state primary school. Parents were given the opportunity to opt-out, and all children provided verbal consent to take part in the study. The study was cross-sectional in design, with 45 children in Year 1 (5-6 years), 45 children in Year 3 (7-8 years), and 45 children in Year 5 (9-10 years); a total of 135 children. This enabled age group-level comparisons to be made across children who were receiving formal mathematics and science education, and for whom considerable developmental changes in domain-general abilities and FI were expected. The gender split in the different age groups was marginally non-uniform, $\chi^2(1) = 5.75, p = .056$ (**Table 1**), and reflected the gender distribution in the school itself. The inclusion criterion was that participants did not have a statement of Special Educational Needs and Disabilities.

Design and procedure

Testing took place at the participants' primary school during lesson times. This was part of a larger test battery which the children completed over three or four sessions. Each task was explained to the participants immediately prior to them attempting the activity. All tasks began with a practice block, which participants were required to pass before proceeding with the experimental trials. The scores on the various tasks were not standardised; age or Year were included as variables in the analyses. Computerised stimuli were presented via MATLAB (R2010b), using the Cogent toolbox (http://www.vislab.ucl.ac.uk/cogent_2000.php), on a 12-inch Dell laptop.

Field independence tasks

Child Embedded Figures Test (CEFT; Karp & Konstadt, 1963). In order for accuracy data to be comparable across all the participants, the same sub-set of 13 images was presented to all participants. The stimuli were selected according to accuracy data from a study in primary school children (Amador-Campos & Kirchner-Nebot, 1997) to include a range of difficulty levels across both target shapes. The target shape was visible throughout the task to reduce the influence of WM (Booth, 2006; Huygelier, Van der Hallen, Wagemans, de-Wit, & Chamberlain, 2018). Participants indicated that they had found the embedded shape by pointing to it. Participants had a maximum of 30 seconds to respond, consistent with some other studies with child participants (e.g. Pellicano, Maybery, Durkin, & Maley, 2006). A percentage accuracy score was calculated. Reliability of the CEFT is between .83 and .90 (Karp et al., 1963), however no reliability data is available for the version used in this study.

Design Organisation Test (DOT; Killgore & Gogel, 2014). This is a pen-and-paper version of the Block Design subtest of the Wechsler Adult Intelligence Scale (WAIS-III; Wechsler, 1997). Participants had to identify which numbered pieces fitted together to create a larger pattern, and then write those numbers in an empty grid. Based on a pilot study, participants were given three minutes to complete as much of the sheet as possible, rather than the two minutes allocated for adult participants (Killgore & Gogel, 2014). A total score was calculated by counting the number of correctly identified small square. Reliability of the DOT in adults is excellent ($r = .91$, Killgore & Gogel, 2014).

Cognitive measures

IQ. General visuo-spatial ability was measured using Raven's Coloured Progressive Matrices (RCPM; Raven, Raven & Court, 2003), which has a reliability of .82 (Carlson & Jensen, 1981). General verbal ability was measured by assessing children's receptive vocabulary using the British Picture Vocabulary Scale III (BPVS III; Dunn, Dunn, Styles & Sewell, 2009). BPVS-III norms for individuals aged 3-16 years indicate excellent reliability of .91. A mean general intelligence (IQ) measure was calculated by averaging z-transformed raw scores on the Raven's and BPVS.

Working memory. Visuo-spatial WM (VSWM) was measured using a computerised backwards spatial span task. The task used a 3x3 grid of lily pads where participants used a mouse to retrace in reverse order a frog's sequence of jumps (**Figure 1A**). Verbal WM (VWM) was measured using a backwards digit span task. For both WM tasks, children began the experimental trials with a sequence length of two. Each sequence length was repeated four times, and each new block increased in sequence length by one. If children made two or more errors in that block, the task stopped. The score on these tasks was the total

number of sequences correctly recalled. These measures were kept separate to enable identification of any differential effects of verbal and visuo-spatial WM. Test/retest correlations partialling out Year were $r = .536$ for the VWM and $r = .357$ for the VSWM, which were calculated from a separate study where 300+ Years 3 and 5 children completed the tasks at a 3 to 5.5 month interval,.

Inhibitory control. Semantic IC was measured using a computerised Animal Size Stroop task (Merkley, Thompson, & Scerif, 2016). Participants were asked to identify which of a pair of animals was the largest in real life by pressing the C- or M-key on a keyboard using their left or right hand respectively. Trials could either be congruent, where the relative size of the animal images matched the relative size in real life, or they could be incongruent and require children to inhibit the size of the image (**Figure 1B**). Each participant completed two blocks of 36 trials, using a pool of four large and four small animals with an equal number of congruent and incongruent trials. Children were asked to respond as quickly, but as accurately, as they could. An IC score was calculated as the percentage difference between congruent and incongruent RT trials, with positive scores denoting a greater RT cost of incongruent trials. Spearman-Brown split-half analysis was .379.

Mathematics and Science measures

Mathematics. Mathematics ability was assessed using two subtests of the Wechsler Individual Achievement Test-II (WIAT-II; Wechsler, 2002). Mathematical Reasoning is verbally administered and tests reasoning through word problems; Numerical Operations is a pen-and-paper test of counting and computation (Meyer, Salimpoor, Wu, Geary, & Menon, 2010). As they assess different mathematical skills, and therefore may differentially

relate to disembedding and segmenting, the subtest scores were kept as separate variables in the analyses. The standard testing and scoring procedures of the WIAT-II were used, where the starting point of the task was determined by age, and trials continued until participants made errors in six consecutive questions. A total score was derived from the number of correct answers attempted plus a score for the easier questions not attempted. Test/retest reliability ranges from .85 to .98 for both subtests (Wechsler, 2002).

Science. In the absence of a suitable standardised test, science ability was assessed using a test designed for this study which can be viewed here: <https://osf.io/d58ht/>. Questions were based on content from the current UK National Curriculum and were designed to test scientific reasoning and scientific inquiry. To ensure the task was representative of science learning in Years 1, 3, and 5, a question was included from every topic in the curriculum for those Years, with the exception of human development in Year 5. Similar to the BPVS, participants within the same Year started at the same level, but would then attempt more challenging or easier questions depending on their accuracy scores. Each question was worth two marks, which sometimes included two-part or multi-answer questions. A score of eight or more out of 10 on a level enabled progression to the next level; a lower score led children to complete the lower difficulty level until they scored at least eight. Lower levels which were not attempted were credited with full marks. The reliability of this novel task was measured by running a split-half analysis in each Year group separately. The Pearson correlations between the scores were: Year 1: .760; Year 3: .870; Year 5: .798.

Results

Age and gender effects

Correlation analyses revealed there were significant linear associations with age in months for all measures (**Table 2**). Previous research has identified an effect of gender on FI. Here, analyses of covariance (ANCOVAs) with gender as the independent variable (IV) and age in months as the covariate, showed no gender main effects or interactions (all p 's > .140). Gender was therefore not included in further analyses. Additional analyses testing for potential non-linear differences between Years are presented in Supporting Information.

Predictors of field independence

To determine how much variance in the FI measures could be explained by age, IQ, WM and IC, multiple regressions were run with CEFT accuracy and DOT scores as dependent variables (DV), and age in months, IQ, VSWM, VWM and IC as IV (**Table 3**). The models explained a significant amount of variance in each task. Individual differences in CEFT performance across Year groups were driven by general cognitive ability (IQ) and VSWM rather than age. In contrast, individual differences in DOT performance were driven by a combination of IQ, VSWM, and age.

Field independence and achievement in mathematics and science

Correlational analyses indicated that there were strong positive associations between FI, mathematics and science, which remained significant when age in months was partialled out (**Table 2**). As all FI, mathematics and science achievement measures showed strong correlations with IQ and WM, and weak or non-significant correlations with IC (**Table 2**), a series of multiple regressions were run to establish whether the observed associations between FI and mathematics and science were due to overlapping variance with the

cognitive variables (**Table 4**). Age in months, IQ, VSWM, VWM and IC were entered first (Model 1). Then, CEFT accuracy or DOT score were added to establish whether they significantly predicted additional variance (Models 2A and 2B). Model 2A indicated that CEFT accuracy explained a significant amount of additional unique variance for Mathematical Reasoning and science achievement. In contrast, the DOT score in Model 2B explained additional variance in Numerical Operations only. IQ and age were also significant predictors in the models, with VWM predicting performance on Mathematical Reasoning as well as Numerical Operations in Model 2B only. Additional analyses assessed whether associations differed between Year groups (see Supporting Information).

Discussion

Higher FI scores associate with higher achievement in mathematics and science (e.g. Alamolhodaei, 2002; Buriel, 1978; Tinajero & Paramo, 1997). However, as studies rarely investigate the influence of covariates such as IQ and executive functions, the cognitive processes underpinning these relationships have not been fully explored, particularly in primary school age children. This study found strong, positive correlations between disembedding and segmenting measures and mathematics and science tests, in line with previous research. After accounting for variance associated with significant IQ and executive function predictors of mathematics and science performance, individual differences in FI explained further variance in scores.

One aim of this study was to gain a clearer picture of the predictors of individual differences in two tasks measuring FI in children aged 5-10 years, as well as of the correlations observed between these two tasks. After controlling for age, there was only a moderate correlation between the two FI tasks, which may result from the contrasting

processes (disembedding and segmenting) involved in the separation of the target from its context in these two tasks. Higher IQ and higher VSWM scores were the only significant predictors of CEFT scores. In contrast, individual differences in DOT scores were explained by IQ, VSWM, and age. In the CEFT, participants have to hold a single target image in mind while they search for a match in the complex figure, a process that likely recruits VSWM. Indeed neuroimaging research has identified activations in the frontal regions associated with VSWM during EFT completion (Damarla et al., 2010; Lee et al., 2007; Ring et al., 1999). Further evidence from research in adults showed that EFT performance was diminished when participants performed a secondary VSWM task concurrently (Miyake et al., 2010). The DOT has a more complicated series of steps required to complete the task, including segmenting the elemental parts, identifying and matching the elemental pattern, and then writing the correct number in the appropriate space in the grid, which may explain why age contributes to individual differences in performance. Although VWM correlated with both the CEFT and DOT, in line with previous research in children (Alloway & Alloway, 2010; Guisande et al., 2008), it was not a significant predictor of either FI measure when the additional general cognitive measures were included. This contrasts with our tentative prediction of a closer link between FI and VWM than VSWM, and may be explained by differing task requirements and a lower mean age in the present study than in the neuroimaging study by Lee and colleagues (Lee et al., 2007). We believe this is the first study to give us a more complete understanding of the general cognitive abilities underlying FI and furthermore, identifies important differences between tasks measuring disembedding and segmenting.

The second aim of this study was to examine the nature of the relationship between FI and mathematics and science. In line with our prediction, and in support of previous

research (e.g. Leo-Rhynie, 1985; Tinajero & Paramo, 1997), there were strong positive associations between FI and mathematics and science performance. However, the FI tasks and academic tests also significantly correlated with IQ, WM, and IC (to a lesser extent), suggesting that it might be these underlying cognitive abilities which explain the relationships. Note that lower associations with IC may be due to the lower reliability of the IC measure. After controlling for age, IQ, WM, and IC, the CEFT explained additional variance on the Mathematical Reasoning and science tests, and the DOT explained additional variance on the Numerical Operations test. This indicates that although some of the relationship between FI and mathematics and science can be explained by overlapping variance with general cognitive abilities, there were additional elements of disembedding that were important for Mathematical Reasoning and scientific achievement, while segmenting was important for Numerical Operations only.

It is possible that disembedding explained performance on Mathematical Reasoning and science due to the inherent need to decontextualise concepts in these tests. In contrast, the written procedural maths questions in Numerical Operations were not embedded in a context, but required the segmentation of place value columns and operation symbols as well as an understanding of abstract mathematical concepts. Contrary to expectation, we did not find a stronger relationship between FI and mathematics and science with age. Although there was a main effect of Year on all variables, the only significant interaction was revealed when predicting Numerical Operations from CEFT. The association was weaker in Year 1 children than in the older children. This may suggest that younger children do not engage similar cognitive processes when completing these two activities, or it may be driven by a lack of variance in Numerical Operation scores in that Year, highlighting the difficulty of finding a written mathematics test suitable across a wide age range.

The finding that an ability to identify and isolate target information from complex stimuli associates with mathematics and science achievement has potential implications for mathematics and science education. Children aged 5-10 years may benefit from information being presented in a clear, non-cluttered way, with attention being drawn to key areas of focus (Fisher, Godwin & Seltman, 2014; Harp & Mayer, 1998). This would enable children to access the target information more easily from within the context of the whole page. Performance may also be improved by encouraging children to selectively attend to important parts of a stimulus, such as a changing operation symbol in a column of number sentences, without being distracted by the whole. Additionally, in order to encourage the decontextualisation of concepts, it may be useful to present concepts in a number of contexts so that commonalities can be identified (Ainsworth, 2008).

Conclusion

This study is the first to examine a number of predictors (age, IQ, WM and IC) of two tasks measuring FI, thus deepened our understanding of the cognitive processes underlying FI. Furthermore, we have identified that the positive relationships between FI and both mathematics and science are partially due to overlapping variance with age, IQ, and WM. However, there are also specific, unique contributions to performance, reflecting the different levels of disembedding and segmenting involved in different mathematics and science tests.

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Tables

Table 1: Participant demographics.

	Year 1	Year 3	Year 5
Number of participants	45	45	45
Number of male : female	16 : 29	27 : 18	24 : 21
Average age in months (SD)	68.62 (3.26)	91.84 (3.47)	115.44 (3.62)

Table 2: Pearson's correlations between performance on Children's Embedded Figures Test (CEFT), Design Organisation Test (DOT), IQ, working memory (WM), and inhibitory control (IC) measures, and mathematics and science tests above the diagonal, and partial correlations controlling for age in months below the diagonal. * $p < .05$, ** $p < .01$, *** $p < .001$. Significant effects are highlighted in bold.

	CEFT	DOT	Mathematical Reasoning	Numerical Operations	Science	IQ	Visuo-spatial WM	Verbal WM	IC	Age
CEFT		.624 ***	.694 ***	.641 ***	.650 ***	.667 ***	.608 ***	.587 ***	-.120	.609 ***
DOT	.323 ***		.749 ***	.741 ***	.724 ***	.748 ***	.691 ***	.568 ***	-.146	.744 ***
Math. Reas.	.422 ***	.340 ***		.858 ***	.832 ***	.875 ***	.709 ***	.716 ***	-.189 *	.842 ***
Num. Op.	.326 ***	.370 ***	.581 ***		.773 ***	.778 ***	.678 ***	.658 ***	-.167	.793 ***
Science	.307 ***	.236 **	.377 ***	.280 **		.828 ***	.637 ***	.629 ***	-.172 *	.869 ***
IQ	.370 ***	.363 ***	.600 ***	.371 ***	.413 ***		.674 ***	.696 ***	-.235 ***	.817 ***
Visuo-spatial WM	.320 ***	.358 ***	.312 ***	.283 **	.083	.250 **		.632 ***	-.150	.699 ***
Verbal WM	.336 ***	.202 *	.457 ***	.346 ***	.230 **	.417 ***	.353 ***		-.277 **	.621 ***
IC	.028	-.040	.012	.028	.060	-.082	.017	-.174 *		-.232 **

Table 3: Hierarchical regressions with DV of Children’s Embedded Figures Test (CEFT) and Design Organisation Test (DOT) and IV of age, IQ, working memory (WM) and inhibitory control (IC). Significant effects are highlighted in bold.

	CEFT Accuracy		DOT score	
	β	p	β	p
Age in months	.077	.501	.287	.004
IQ	.351	.004	.351	.001
Visuo-spatial WM	.214	.023	.268	.001
Verbal WM	.177	.056	-.013	.868
IC	.062	.341	.039	.472
R²	.508	< .001	.648	< .001

Table 4: Multiple regressions to identify unique variance of field independence. DVs were Mathematical Reasoning, Numerical Operations and science scores; age in months, IQ, verbal working memory (VWM), visuo-spatial working memory (VSWM) and inhibitory control (IC) were entered in the first model, and then Children's Embedded Figures Test (CEFT) (A) or Design Organisation Test (DOT) (B) in the second model. Significant CEFT and DOT effects are highlighted in bold.

	Mathematical Reasoning			Numerical Operations			Science		
	R^2	β	p	R^2	β	p	R^2	β	p
Model 1	.835		< .001	.706		< .001	.801		< .001
Model 2A	.841		< .001	.712		< .001	.807		< .001
Age		.319	< .001		.389	< .001		.583	< .001
IQ		.414	< .001		.233	.015		.297	< .001
VSWM		.057	.297		.101	.171		-.062	.305
VWM		.141	.009		.137	.057		.046	.429
IC		.043	.249		.044	.377		.050	.225
CEFT		.111	.029		.112	.100		.113	.044
Model 2B	.837		< .001	.721		< .001	.803		< .001
Age		.305	< .001		.338	< .001		.568	< .001
IQ		.426	< .001		.199	.036		.308	< .001
VSWM		.060	.288		.069	.351		-.059	.339
VWM		.161	.003		.159	.023		.067	.249
IC		.047	.214		.043	.383		.054	.196
DOT		.077	.202		.208	.009		.082	.218

Figure

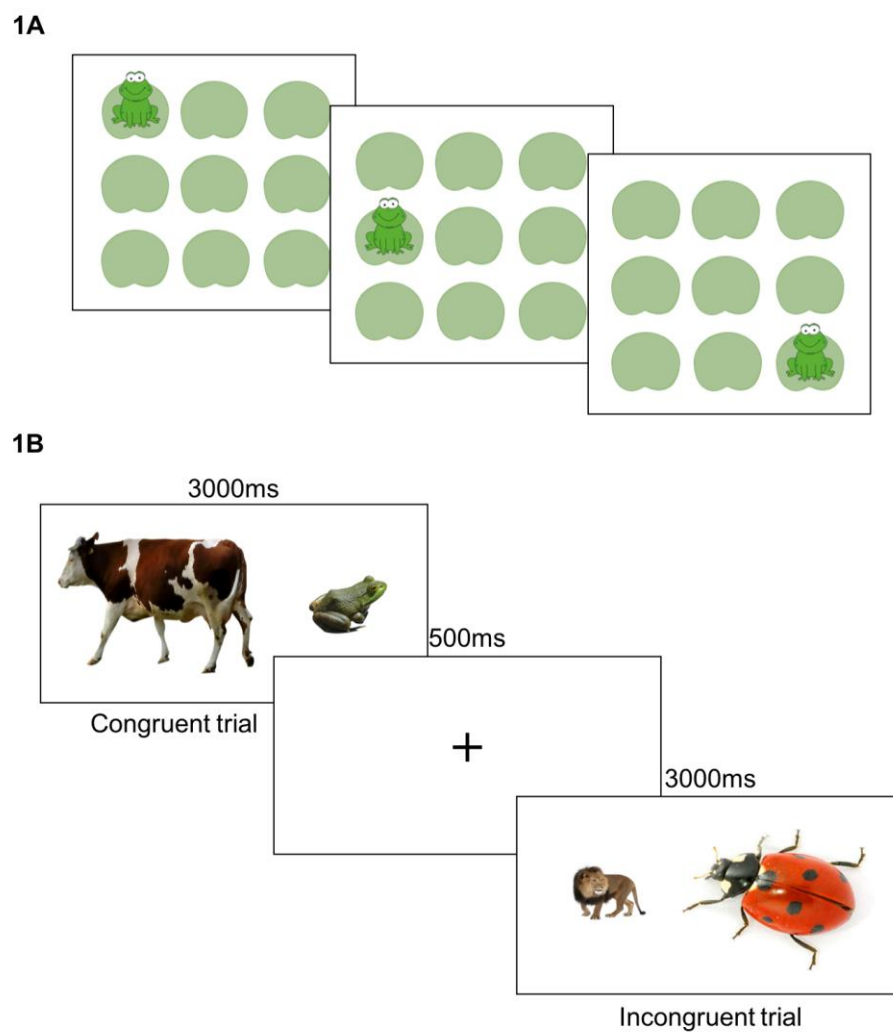


Figure 1: (A) Example sequence from the visuo-spatial working memory backwards span task. Children responded by clicking on the lily pads to retrace the sequence of jumps made by the frog, in reverse order. (B) Example stimuli from the Animal Size Stroop Task. Children responded by pressing letter keys to identify the big animal in real life.

Field Independence associates with mathematics and science performance in 5- to 10-year-olds after accounting for domain-general factors

Supporting Information

One-way ANOVAs showed that field independence, mathematics, and science performance all improved with Year (**Table S1**). Two-way gender x Year ANOVAs did not show any significant main effect of interaction with gender.

Table S1: Estimated margin means (SE) and main effects of Year for Children's Embedded Figures Test (CEFT), Design Organisation Task (DOT), IQ, working memory (WM), inhibitory control (IC), and mathematics and science tests. Significant effects are highlighted in bold.

	Year 1	Year 2	Year 3	Main effect of Year (df = 2, 132)
CEFT accuracy %	33.2 (2.2)	49.4 (2.2)	60.3 (2.2)	$F = 38.97, p < .001, \eta^2_p = .371$
DOT total (max 56) ^a	10.9 (0.9)	17.2 (0.9)	26.7 (0.9)	$F = 79.74, p < .001, \eta^2_p = .547$
IQ (mean)	-1.0 (0.8)	0.2 (0.8)	0.8 (0.8)	$F = 136.93, p < .001, \eta^2_p = .675$
Visuo-spatial WM (max 26) ^a	4.3 (0.4)	7.8 (0.4)	11.0 (0.4)	$F = 61.35, p < .001, \eta^2_p = .482$
Verbal WM (max 26) ^a	5.4 (0.3)	7.8 (0.3)	9.5 (0.3)	$F = 45.59, p < .001, \eta^2_p = .392$
IC RT cost %	0.14 (0.02)	0.09 (0.02)	0.09 (0.02)	$F = 5.08, p = .007, \eta^2_p = .071$
Reasoning (max 67) ^a	17.2 (0.8)	31.5 (0.8)	39.5 (0.8)	$F = 182.34, p < .001, \eta^2_p = .734$
Numerical (max 54) ^a	8.4 (0.6)	12.8 (0.6)	21.2 (0.6)	$F = 128.42, p < .001, \eta^2_p = .661$
Science (max 60) ^a	11.1 (1.1)	26.4 (1.1)	44.0 (1.1)	$F = 204.77, p < .001, \eta^2_p = .756$

^a Total score

Further analyses were run to establish whether the relationships between field independence and mathematics and science remained constant across Year groups. Dummy

Year variables were created and entered in regression analyses with mathematics or science measures as dependent variables (DVs) and CEFT or DOT as independent variables (IVs) in block 1. In block 2, interaction terms between the dummy Year variables and Children's Embedded Figures Test (CEFT) or Design Organisation Task (DOT) scores were entered stepwise. The only significant interaction term was observed when predicting Numerical Operations from CEFT (Year 1 x CEFT, $\beta = -.177, p = .018$), and indicated that the association was weaker in Year 1 than in Years 3 and 5 (**Figure S1**). No other interaction term was selected (all p 's $> .100$) indicating that the other associations did not differ across the Years.

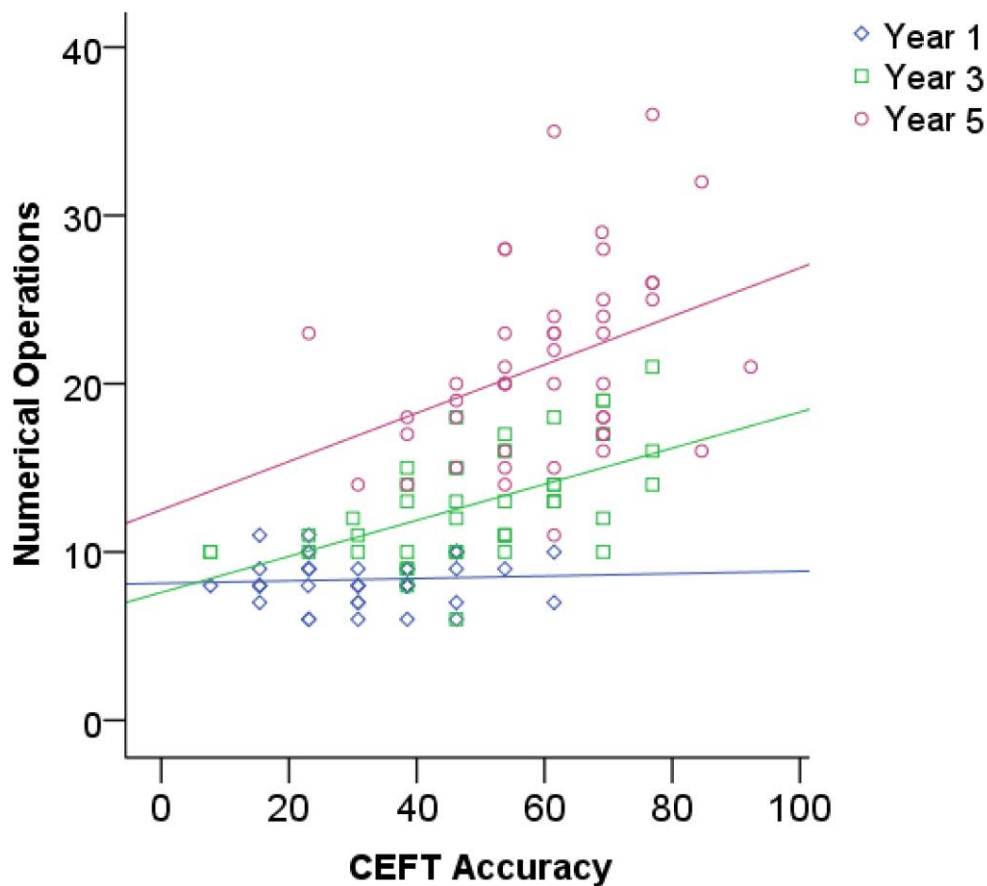


Figure S1: Scatterplot of Numerical Operations score as a function of Children's Embedded Figures Test (CEFT) accuracy and Year.